Properties of the Gray Hydromorphic Soils of the Hawaiian Islands[1]

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THE GRAY HYDROMORPHIC SOILS of the Hawaiian Islands are dark-colored, poorly drained, sticky plastic clays. These soils owe their morphology to their hydromorphic condition produced by their naturally poor drainage. This poor drainage of the soil has developed poor aeration, reducing conditions, and a reduction of the biological activity, which has prevented the full influence of all soil-forming factors essential to normal soil development.

The gray hydromorphic soils are characterized by a horizon that is mottled gray, brown, and yellow by periodic waterlogged conditions. Cline *et al.* (in press) have divided this intrazonal soil group into three soil families, based on the degree of expression of the hydromorphic characteristics. The soils belonging to the Honouliuli family are the least hydromorphic. They have a grayish-brown, clayey B horizon that is mottled below 18 to 20 inches. The water table is generally not near the surface, and the mottling appears to be the result of impeded downward movement of water rather than a water table. The soils belonging to the Kalihi family are more strongly hydromorphic. The mottling in these soils occurs immediately below the A_1 horizon. The soils of the Kaloko family are the wettest of the group. Mottling appears in the A_1 horizon, and these soils have a water table near the surface most of the year.

The gray hydromorphic soils are found on the islands of Kauai, Oahu, Molokai, and Maui. They have developed on the islands which are the oldest geologically. They are usually found at the lower elevations on these islands and are associated with well-drained soils in the advanced stages of weathering—the latosols. The gray hydromorphic soils have properties which make them similar to the paddy soils (water-logged soils) and to the dark magnesium clays (tropical black soil) of the semi-arid regions. All of these soils (gray hydromorphic, paddy, and dark magnesium clay) exhibit similar physical properties in that they are sticky plastic clays.

The sticky plastic properties of the gray hydromorphic soils make their management very difficult. The most probable reasons for the extreme sticky and plastic nature of these soils are, first, the nature and percentage of clay in these soils, and, second, the presence of a condition in the soil which would cause the soil to exist in a deflocculated condition. This latter condition has been noted in many locations where the amount of exchangeable sodium in the soil has been high. Observations (Von Kreybig, 1935) indicate that when the amount of exchangeable magnesium in a soil is very high, and the sum of the exchangeable calcium plus exchangeable magnesium approaches 100 per cent saturation of the soil, the properties of the soil will be similar to those of a "sodium soil."

Usov (1937) described soils in Russia, having more than 30 per cent of their exchange capacity filled with magnesium, which are plastic and exhibit other "sodium soil"

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characteristics, including a decrease in the percolation rate. Kudrin and Rozanov (1940) reported a magnesium sierozem which was derived from both high magnesium parent materials and high magnesium ground waters. Such soils possessed a poor physical structure, low porosity, and a generally poor physical condition. Von Kreybig (1935), while studying Hungarian soils, found that 20 to 25 per cent magnesium saturation produced soil properties which were similar to those of soils having a high sodium saturation.

Several workers have reported evidence of magnesium salinization in Hawaiian soils. The Hawaiian soils have developed on basaltic rocks which are very rich in olivine, a magnesium-iron silicate. This would provide a source of magnesium for ground waters which would ultimately find their way to the areas of restricted drainage. McGeorge (1930) pointed out that exchangeable magnesium was increasing in certain soils where the irrigation water contained appreciable amounts of magnesium salts. Hance and Stewart (1927) reported a low calcium–magnesium ratio in certain poorly drained Maui soils which have a high base saturation. This would indicate the presence of magnesium salts. Sherman *et al.* (1947) showed that dolomitization occurs in certain calcareous semi-arid Hawaiian soils where the ground water is rich in magnesium salts. Results of the soil research work at the University of Hawaii have established that, when a soil has more than 30 per cent of its exchange capacity occupied by magnesium, and the sum of the exchangeable calcium plus exchangeable magnesium amounts to more than 90 per cent of the exchange capacity, the soil will exist in a dispersed condition. All soils possessing this relationship are black, sticky plastic clays. The soils of the gray hydromorphic group are of this type.

The purpose of this investigation is to study the factors which give rise to the plastic properties of the gray hydromorphic soils. The influence of such factors as cation exchange capacities, per cent magnesium saturation, calcium–magnesium ratios, organic matter content, amount of clay-size particles, and the nature of the clay minerals on the plasticity of the soil were studied in this investigation.

METHOD OF ANALYSIS

Soil samples were collected from typical soils of the three soil families belonging to the gray hydromorphic group. All of the soils used in this investigation were collected on the island of Oahu. Most of the samples were collected from Ewa, areas adjacent to Pearl Harbor, Wailupe, Koko Head, and the windward areas on the north side of Oahu.

The chemical analysis of the soils was made by standard methods. In the determination of exchange capacity and exchangeable cations, neutral normal ammonium acetate solution was used as the replacing agent. The water-soluble salts were removed by leaching the soil with a 40 per cent ethyl alcohol solution until the leachate was free of chlorides and sulfates prior to the ammonium acetate extraction. Alcoholic solutions of ammonium acetate were used on soil samples containing carbonates, according to the procedure described by Magistad and Burgess (1928).

The plastic index or plastic number—the range of soil moisture over which the soil exhibits plastic properties—was determined by the method proposed by Baver (1932). The upper and lower plastic limits were determined by this procedure, and the difference is referred to as the plastic number.

Organic matter was determined in these soils by the method developed by Walkley (1935).

CHEMICAL AND PHYSICAL PROPERTIES OF THE GRAY HYDROMORPHIC SOILS

The cation exchange capacity, exchangeable cations, per cent magnesium saturation, organic matter content, and plastic number of typical soils of the three soil families of the gray hydromorphic group are given in Table

TABLE 1

THE CHEMICAL COMPOSITION OF THE EXCHANGE COMPLEX, ORGANIC MATTER CONTENT, AND MEASUREMENTS OF PLASTICITY OF TYPICAL GRAY HYDROMORPHIC SOILS

Sample	*p*H	Cation exchange capacity	Exchange-able calcium	Exchange-able magnesium	Per cent Mg saturation	Ca:Mg ratio	Per cent organic matter	Per cent soil particles less than .005 mm.	Upper plastic limit	Lower plastic limit	Plastic number
		m.e./100 g.	*m.e./100 g.*	*m.e./100 g.*							
Honouliuli family											
Hon – 1	7.2	12.8	9.0	3.7	28.9	2.43	2.14	49.2	46.5	34.7	11.8
Hon – 2	6.7	11.0	3.4	3.9	35.5	0.87	0.96	54.5	47.1	33.6	13.5
Hon – 3	7.7	15.5	6.3	4.5	29.0	1.40	1.66	66.5	44.7	32.2	12.5
Hon – 4	7.2	12.7	7.2	4.5	36.2	1.60	1.16	70.6	46.6	30.5	16.1
Hon – 5	7.7	21.3	11.6	10.2	47.9	1.14	2.11	71.0	42.4	25.9	16.5
Kalihi family											
Ki – 1	7.3	27.8	16.1	12.9	46.4	1.25	2.41	52.2	45.5	30.0	15.5
Ki – 2	7.3	28.3	14.8	12.6	44.5	1.18	2.24	54.4	45.7	31.4	14.3
Ki – 3	7.4	24.3	15.3	12.4	51.0	1.23	1.70	63.8	46.5	30.8	15.7
Ki – 4	7.6	25.9	14.3	13.0	50.2	1.10	1.36	62.2	48.6	30.5	18.1
Ki – 5	6.9	31.8	7.9	16.7	52.5	0.47	2.69	58.7	57.4	38.8	18.6
Ki – 6	7.1	29.3	10.1	18.6	63.5	0.54	2.80	66.8	60.6	39.2	21.4
Ki – 7	7.8	41.1	18.2	12.4	30.2	1.47	4.99	64.9	62.3	32.5	29.8
Kaloko family											
Ko – 1	7.8	27.8	12.1	16.0	50.4	0.76	1.51	54.9	43.7	28.5	15.2
Ko – 2	7.4	29.4	14.7	14.1	48.0	1.04	2.66	60.5	47.7	30.9	26.8
Ko – 3	6.5	30.6	15.0	12.6	41.2	1.19	2.76	62.2	54.3	30.2	24.1
Ko – 4	7.8	25.4	11.8	16.9	66.5	0.70	2.48	51.2	44.4	28.2	16.2
Ko – 5	7.7	26.3	15.9	12.4	47.1	1.28	2.04	73.9	54.9	30.7	24.2
Ko – 6	7.4	25.9	16.2	12.0	46.3	1.35	2.55	78.2	58.2	33.4	24.8
Ko – 7	5.9	30.2	17.1	10.4	34.4	1.64	3.37	74.9	72.2	41.8	30.4

1. The lowest cation exchange capacities were found in the soils belonging to the Honouliuli family where the range was from 11.0 to 21.3 milliequivalents per 100 grams. The cation exchange capacities of soils of the Kalihi and Kaloko families range from 24.3 to 41.1 milliequivalents per 100 grams, which are much higher than capacities of the Honouliuli soils. Likewise, the per cent magnesium saturation is the lowest in the soils of the Honouliuli family. The range for all soils was from 28.9 to 66.5 per cent. The ratio of exchangeable calcium to exchangeable magnesium was very variable in each soil family and showed little evidence of any real differences.

The organic matter content of the gray hydromorphic soils varies greatly from soil to soil. These soils have the lowest organic matter content of the Hawaiian soils, as most zonal soils of the islands have an organic matter content higher than 3 per cent. In general, the greater the expression of hydromorphic condition, the greater the organic matter content of the soil.

The soil particles less than 5 microns in size make up the major portion of the particles of these soils. Most of these soils have from 40 to 50 per cent clay-size particles. Thus, all of these soils are clays. The clay content was practically the same for the soils of each soil family.

The plastic numbers of these soils ranged from 11.8 to 30.4. The highest values for the plastic number were found for the soils of the Kaloko family and the lowest for the soils of the Honouliuli family. This would indicate that the plastic properties were developed to the greatest extent in the soils having the greatest hydromorphic conditions.

INTERRELATIONSHIP OF PROPERTIES TO PLASTIC NUMBER

The data presented in Table 1 indicate that some of the chemical properties are related to the plastic number. Figure 1 shows the relationship between the cation exchange capa-

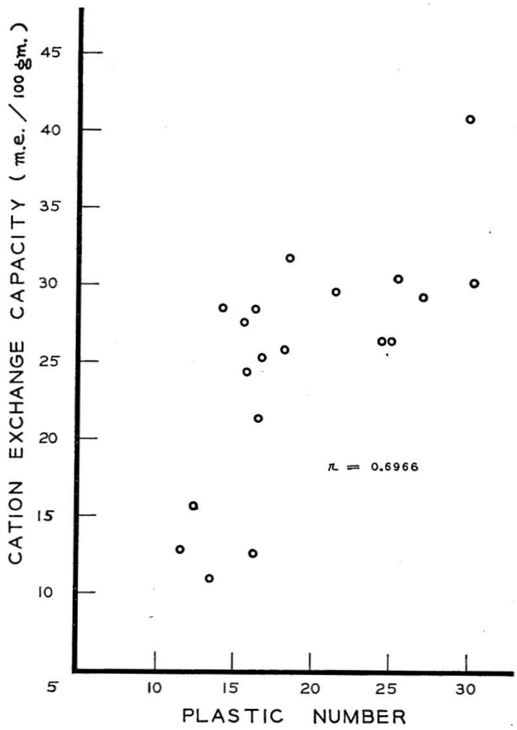

FIG. 1. The relation between cation exchange capacity in milliequivalents per 100 grams and plastic number of gray hydromorphic soils.

city of the soil and the plastic number. This relationship is very significant. Statistical analysis of the data shows a correlation coefficient of .697.

The data presented in Figure 2 show the relationship between per cent magnesium saturation and plastic number. There appears to be no real relationship between these factors. Likewise, there is no relationship between the ratio of exchangeable calcium to exchangeable magnesium and the plastic number. It is apparent that, since there is an observed relationship between per cent magnesium saturation and a dispersed condition of the soil, some other soil factor must play a major role in the development of the plastic properties of the clay.

The relationship between the organic matter content of the soil and the plastic number of the soil is shown in Figure 3. A correlation coefficient of .726 indicates a highly significant relationship between these two factors. Baver (1928) has shown that the plastic number of a soil increases as the organic matter content of the soil increases. The plasticity of these soils and their impermeability is much greater than those of other soils of corresponding clay and organic matter content.

In order to study the influence of organic matter on the plastic number, the organic matter was removed from a soil of the Kalihi family by treatment with hydrogen peroxide. Samples of the treated and untreated soil were placed in percolation tubes, and the percolation rate of distilled water through the samples was measured. Since there is an observed effect of per cent magnesium saturation on the physical condition, the level of magnesium was altered to determine the role of interrelationship between level of exchangeable magnesium and organic matter content on the impermeability of the soil. The data are presented in Figure 4. The removal of the organic matter increased the rate of percolation of water through the soil. Percolation of water through the sample possessing the organic matter progressed at a steady rate, while in the untreated soil the rate of percolation was fast at the beginning and then became progressively slower. The soil with low magnesium had the fastest percolation rate and the soil with the high magnesium level percolated in the same fashion as the untreated soil. The progressively slower percolation of the untreated sample and of the soil having a high magnesium level can be attributed to an increase in the dispersion of the colloidal system. Thus, the effect of both organic content and high magnesium level appears to be on the state of dispersion of the colloidal system, which can be increased by the degree of hydration.

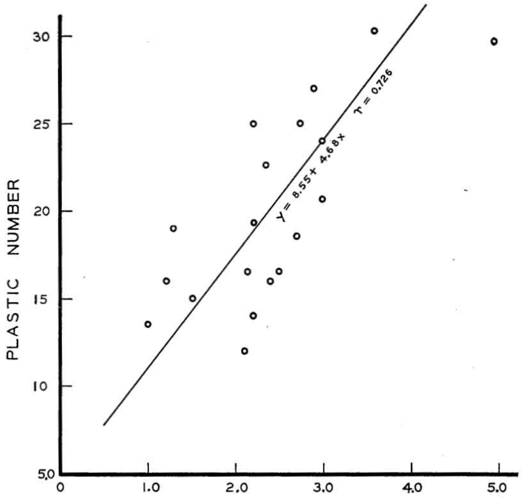

FIG. 3. The relationship between content of organic matter in the soil and plastic number of gray hydromorphic soils.

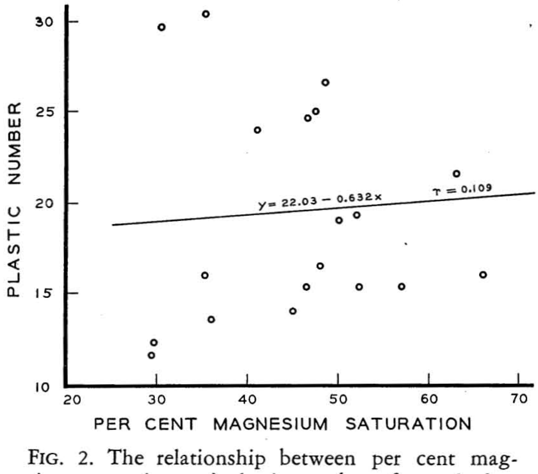

FIG. 2. The relationship between per cent magnesium saturation and plastic number of gray hydromorphic soils.

NATURE OF THE CLAY FRACTION

The chemical composition of the clay fraction of the gray hydromorphic soils is given in Table 2. There is a great similarity in the analysis of the clays of these soils. The silica content ranges from 38.1 to 41.2 per cent. Likewise, the aluminum oxide and iron oxide content of the clays of the three soils show very little variation. The low content of magnesium oxide in the crystal lattice rules out the possibility of magnesium substitution into lattice position being the cause of the plastic properties.

The type of clay minerals in the clay frac-

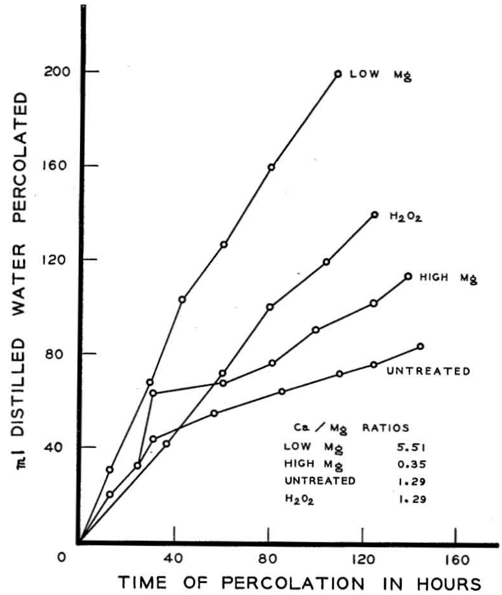

FIG. 4. The influences of organic matter content and exchangeable magnesium level on the rate of percolating water.

tion has been identified by differential thermal methods developed by Norton (1939). The thermal curves show that the dominant clay mineral in the Kalihi and Kaloko soils is of the montmorillonite type. The soils of the Honouliuli family have appreciable amounts of kaolinite. This would account for their lower cation exchange capacity. Matsusaka and Sherman (1950) found that the titration curves of the gray hydromorphic soils were similar to those of montmorillonite clays.

DISCUSSION

The results of this investigation have brought out the fact that there are several factors which influence the plastic properties of a soil. In general the type of clay, the organic matter content, and adsorbed cations are the most important. The exact details of the mechanism of magnesium-induced impermeability and plasticity are not known. It is suspected that hydration of the exchangeable magnesium ion is greater in the presence of certain humates and that this hydration results in a dispersion of the clay and organic matter. However, this dispersion is dependent upon a type of clay which perhaps must possess certain external and internal surface characteristics. The results of this study would indicate that only a montmorillonite clay can develop these plastic properties with these factors.

Humus influences the plastic properties of a magnesium-saturated clay by forming a complex or by establishing conditions which enable magnesium to become hydrated. Humate attached to the clay indirectly through the magnesium could widen the Helmholtz layer and cause an increase in the

TABLE 2
THE CHEMICAL COMPOSITION OF THE CLAY FRACTION OF TYPICAL SOILS OF THE GRAY HYDROMORPHIC GROUP

Soil family	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO
	per cent	*per cent*	*per cent*	*per cent*	*per cent*	*per cent*
Honouliuli A Horizon	38.10	23.02	14.08	1.80	1.02	1.26
Kalihi A Horizon	41.07	25.12	11.80	1.52	0.50	0.99
Kalihi B Horizon	41.20	25.30	10.65	1.34	0.66	0.91
Kaloko A Horizon	39.81	25.20	14.70	1.85	0.44	0.80
Kaloko B Horizon	39.02	26.27	13.90	1.52	0.29	0.81

zeta potential. This would call for an inherent characteristic of magnesium alone or in combination with unique surface phenomena of the type of clay mineral in the soil.

Both the nature and amount of clay present in a soil play an important role in the plastic properties of the soil. The clay particles of the montmorillonite type of clay, which are plate-like structures, secure their plasticity from a small film between two particles which easily permits sliding along the axis of the longitudinal plane but requires a considerable force to pull the particles apart. An equilibrium of the component factors is set up in the clay fraction of the soil. The following are the component factors concerned:

(1) Clay. The clay has its maximum plastic properties only when the clay is completely dispersed and when water is present in sufficient quantities to fill the space between all of the particles to a uniform degree of thickness. The thickness will determine the viscosity of the plastic state. The ability of the clay to attract water will be determined by the type of clay and its charge (cation exchange capacity) which in turn will be determined by the characteristics of its crystal lattice and internal and external surface area.

(2) Exchangeable magnesium. The amount of exchangeable magnesium, which has the maximum observed potential dispersing power, is limited in its dispersing power by the amount of exchangeable calcium (a flocculating agent) present or by the amount of organic matter, which increases dispersive properties of magnesium by increasing its hydration.

(3) Organic matter. The amount and nature of the organic matter present in the soil have a maximum potential as a co-dispersing agent. The dispersing power of the magnesium is modified by the amount of organic matter present in the soil.

One of the observed characteristics of the gray hydromorphic soils is that exchangeable magnesium occupies 30 or more per cent of the cation exchange capacity. It has been observed that soils having this level of magnesium saturation always possess a high degree of plasticity when the calcium–magnesium ratio approaches equivalence. Since neither the per cent magnesium saturation nor the calcium–magnesium ratio is correlated with the plastic number of the soil, it is believed that neither of these factors is limiting. The per cent organic matter and the cation exchange capacity of the soil are correlated to a high degree to the plastic number. This would indicate that the two main factors involved in the development of the plastic properties are the amount of organic matter present and the inherent properties of the clay which is a montmorillonite type of clay mineral. The clay fraction of the gray hydromorphic soils does not possess an excessive electrical charge which can cause dispersion. The dispersion of the gray hydromorphic soils appears and disappears as the exchangeable magnesium, the organic matter, and the water hulls of hydration are added or removed.

SUMMARY

The gray hydromorphic soils of the Hawaiian Islands are capable of becoming dispersed and plastic when the per cent magnesium saturation exceeds 30 per cent in the presence of organic matter, providing the ratio of exchangeable calcium to exchangeable magnesium is approximately unity.

The calcium–magnesium ratio and the per cent magnesium saturation are not correlated with the plasticity of the soil. The content of organic matter and the cation exchange capacity of the soil are significantly related to the development of the plastic properties.

A decrease in the amount of exchangeable magnesium present or the removal of the organic matter from these soils increases the rate of percolation of water through these soils, which indicates a decrease in its degree of dispersion. Since all soils do not respond

in this manner, the inherent properties of the clay must be responsible for these attributes. The clay has been identified as a montmorillonite type by differential thermal methods.

REFERENCES

BAVER, L. D. 1928. The relation of exchangeable cations to the physical properties of soils. *Amer. Soc. Agron., Jour.* 20: 921–941.

——— 1932. The use of the Troemmer balance for measuring upper plastic limit of soils. *Amer. Soc. Agron., Jour.* 24: 686–690.

CLINE, M. G., *et al.* In press. Soil survey of the Hawaiian Islands. U. S. Dept. of Agr.

HANCE, F. E., and G. R. STEWART. 1927. Replaceable bases in the soils of central Maui. *Hawaii. Planters Rec.* 31: 342–354.

KUDRIN, S. A., and A. N. ROZANOV. 1940. The characteristics of sierozem containing a high content of magnesium. *Pedology* 2: 52–65.

MAGISTAD, O. C., and P. S. BURGESS. 1928. *The use of alcoholic salt solutions for the determination of replaceable bases in calcareous soils.* Ariz. Agr. Expt. Sta., Tech. Bul. 20. 16 pp.

MATSUSAKA, YOSHITO, and G. DONALD SHERMAN. 1950. *Titration curves and buffering capacities of Hawaiian soils.* Hawaii Agr. Expt. Sta., Tech. Bul. 11. 36 pp.

MCGEORGE, W. T. 1930. The chemical and physical properties of Ewa Plantation soils as influenced by irrigation with artesian water. *Hawaii. Planters Rec.* 34: 179–219.

NORTON, F. H. 1939. Critical study of the differential thermal method for the identification of the clay minerals. *Amer. Ceramic Soc., Jour.* 22: 54–63.

SHERMAN, G. DONALD, YOSHINORI KANEHIRO, and CHARLES K. FUJIMOTO. 1947. Dolomitization in semi-arid Hawaiian soils. *Pacific Sci.* 1(1): 38–44.

USOV, N. I. 1937. Effect of adsorbed magnesium on saline properties of soil. *Proc. Conf. Soil Sci.* [*Saratov*] 1: 44–61. (Chem. Abs. 33: 8342, 1939.)

VON KREYBIG, I. L. 1935. Vorkommen, Eigenschaften und Wirtschaftlicher wert von Magnesia und Kaliboden in Ungarn. [*3rd*] *Internatl. Cong. Soil Sci., Trans.* 1: 353–357.

WALKLEY, A. 1935. An examination of methods for determining organic carbon and nitrogen in soils. *Jour. Agr. Sci.* 25: 598–608.